Multi-tone Measurement Infrastructure for Microwave Power Transistor Characterization under Wideband Multi-tone Stimuli

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Abstract-**This paper presents a refined modulated waveform measurement system for the robust characterization of nonlinear microwave devices when driven by broadband multi-tone stimuli. This enhanced system has the ability to present specific, constant impedances, not only to a large number of baseband (IF) components, but also to signals located around the carrier and significant harmonic frequencies. Achieving such comprehensive impedance control across wide modulation bandwidths is critical in allowing the 'emulation' of new power amplifier modes and architectures, and the subsequent waveform characterization of devices operating in these complex and often dynamic impedance environments. The enhanced system is demonstrated through a number of applications: firstly the experimental investigation and baseband optimization of a 10W GaN HEMT under nine-tone excitation, and secondly, the emulation of a modulated Class-J impedance environment that interestingly highlights the presence of separate optimum baseband impedance conditions necessary for the reduction of individual IM products.**

I. INTRODUCTION

The recent rapid development of mobile communications standards has resulted in a growing motivation to develop measurement systems capable of characterizing microwave power devices under realistic modulated stimuli. This is particularly relevant in the context of the highly dynamic RF envelopes that result from the use of modulation schemes such as multicarrier code division multiple access (CDMA) and orthogonal frequency division multiplexing (OFDM), where the coexistence of static and dynamic nonlinear distortion sources in microwave devices and circuits can severely compromise performance, not only in terms of general linearity, but also in terms of how easily such systems can be linearized. The minimization of effects that lead to such problematic distortions relies heavily on the accurate characterization of the microwave power devices used.

It is now widely accepted that the linearity performance of a microwave device is effected by, not only the impedance environment presented at the fundamental and higher harmonic frequencies, but also at much lower baseband frequencies [1]-[3]. In reality, and in response to a simple two-tone excitation, the baseband spectrum constitutes not only the significant baseband components (IF1 and IF2) but also the higher baseband components (IF3, IF4), the presence of which can present a significant design challenge in achieving adequate broadband baseband impedance termination for high linearity. Previous work has highlighted the fact that the variation of baseband impedance over bandwidth is an important problem that needs further investigation to pave the way for the development of future high- efficiency, high -linearity and high -bandwidth communication systems [3]-[4].

The first part of this paper explains the significant measurement system enhancements performed to allow dynamic baseband impedance characterization under complex modulated excitations and quantifies the persistent influence of baseband impedance variation on ACPR performance. It is shown for instance that when a device is subjected to complex 9-tone excitation, a significant linearity improvement can be achieved by synthesizing specific baseband signals, characterized by specific negative baseband impedances, as has already been shown for the two-tone case in [3].

The second part of this paper shows how it is possible to control all significant out-of-band frequency components, particularly at baseband, fundamental and 2nd harmonic, through the significant modification of the measurement system RF architecture and enhancement of measurement dynamic range. These capabilities are then demonstrated through the active synthesis of the fundamental and second harmonic RF loads necessary to emulate a class-J impedance environment under modulated excitation. This new RF load-pull functionality has been achieved using a very-high bandwidth, dual channel arbitrary waveform generator - the Tektronix AWG7000. One motivation behind this analysis is to investigate the effectiveness of using the baseband linearization for novel PAs where the fundamental and harmonic loads presented to the device can be highly reactive.

II. THE ENHANCED MODULATED MEASUREMENT SYSTEM

Earlier work has generally focused completely on understanding the effects of baseband impedance variation over bandwidth, and the active load-pull systems used have been capable of presenting specific baseband impedances to the two most significant baseband components (IF1 and IF2), and measuring RF modulation envelopes generated as a result of simple modulated excitation [4]-[6]. Although effective, these systems are generally limited to two or three-tone excitations due to complexities in the triggering and averaging of complex modulated signals using high-speed sampling oscilloscopes.

A. Improving Dynamic Range - Triggering and Averaging

When measuring CW signals, the sampling oscilloscope is usually triggered from the input signal itself. This sub-sampling

approach becomes impractical for multi-tone signals as each cycle of RF within the modulation envelope is no longer identical, and the waveform pattern no longer repeats on each rising edge of the RF waveform. In order to achieve high measurement speed and a useful dynamic range in the region of 60dB, it was critical that the enhanced modulated measurement system should be able to utilize the on-board averaging capability of the oscilloscope (Tektronix DSA8000).

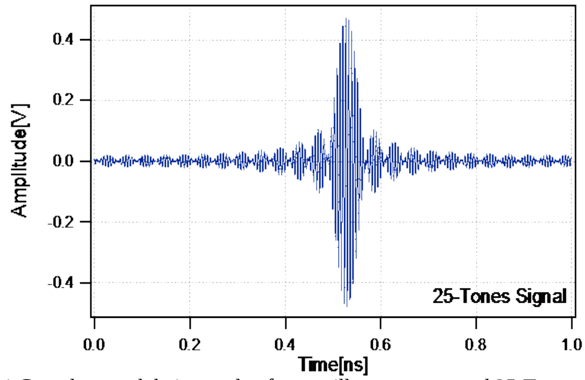

Fig. 1 Complete modulation cycle of on oscilloscope averaged 25-Tones signal at a carrier frequency of 2GHz with 500 kHz tone separation.

When measuring complex modulated signals for the applications presented in this paper, it becomes critical to capture detailed features, both in the individual RF cycles, and the modulated RF envelopes, which can be difficult to achieve using sampling oscilloscopes where the number of horizontal points is limited. Folded and interleaved sub-sampling techniques have been developed and effectively compress the spectra of the captured waveforms, and reduce the number of RF cycles per cycle of modulation. Whilst these maintain the integrity of the captured signal [7], they were found to be problematic for capturing complex modulations.

The accurate triggering of the 4-channel sampling oscilloscope has been achieved here using an Agilent 120MHz arbitrary waveform generator (AWG) to generate high-quality, low-jitter repetitive trigger pulses at the modulation frequency of interest. When established correctly and synchronized with a multi-tone modulated source, complex modulated waveforms can be accurately captured, as depicted in Fig. 1.

B. *Multi-Tone Measurements*

In order to capture multi-tone signals using a standard sampling approach, the high-accuracy trigger was provided at the repetition rate of the modulated sequence. The DSA8000 has only 4000 measurement points making it impractical to capture, in one waveform, all of the relevant information present in a complex multi-sine modulation, so, a new technique was introduced that allowed the sequential capture of 'sections' of a complete modulation cycle, referred to here as “windowing”. In this approach, the oscilloscope is caused to repeatedly trigger at a specific points within the modulation cycle, and by varying precisely the trigger delay and record length, it is possible to isolate and average specific parts of even complex modulation envelopes. Thus, it is possible to step through the modulated waveform, and accurately capture one complete modulation cycle in sufficient detail and accuracy for meaningful analysis.

Each captured, 4000 point window is typically averaged 500 times before being downloaded to a computer ready for assembly and analysis. The formulation given in (1) defines the number of windows (W) required to capture one complete cycle of modulation.

$$W = (2 \cdot (H+1) \cdot f_C) / P \cdot f_M \tag{1}$$

In the above equation, H is the number of required harmonics, f_c is carrier frequency, f_m is modulation frequency and *P* is number of points used, here limited to 4000.

As well as improving dynamic range, this technique has allowed measurement time to be dramatically reduced - for example, it now takes less than 1 minute to completely capture a device’s non-linear response (including baseband and five harmonics) to a 1 MHz modulated 2GHz carrier. The frequency of the tones used to generate the modulation need to be considered carefully however to avoid waveform 'stitching' problems and subsequent spectral re-growth. To demonstrate the improved dynamic range of the enhanced measurement system, a thru measurement was conducted using a 9-tone stimulus with a notch created by progressively suppressing the central tone. For this case, and as can be seen from Fig. 2, the measurement system can measure this tone to approximately 50 dBc. From the same plot, the out-of-band dynamic range is closer to 60 dB, and this is perfectly sufficient to be able to measure the relatively low distortion levels of interest here.

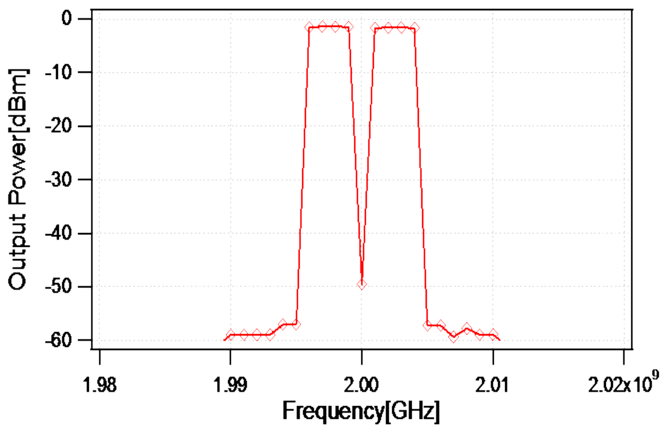

Fig. 2 Measured output spectrum for thru standard using 64 averages with the lowest spectral information.

A closer analysis of measurement system dynamic range for modulations using different numbers of tones, and using 64 averages is shown in Table-1. Increasing averaging beyond this has little effect on the in-band dynamic range as this is eventually limited by the leakage distortion properties of the modulated source. Increased averaging does however reduce the noise floor. One important observation to note is that when the phases of the tones used in the excitation are randomized, the dynamic range of measurement system is slightly reduced. For all measurements, the tone amplitudes were adjusted to ensure a constant peak envelope power.

TABLE I
DYNAMIC RANGE OF MEASUREMENT SYSTEM FOR DIFFERENT MULTI-TONE EXCITATIONS

Fixed Amplitude	**2-Tone (dB)**	**5-Tone (dB)**	**9-Tone (dB)**	**25-Tone (dB)**
Fixed Phase	64	62	60	45
Randomized Phase	61	59	56	39

C. Broadband Active RF and IF Load-pull

Achieving broadband, baseband load emulation, required significant modification to the active load-pull architecture to account for the presence of higher baseband harmonics. This functionality was achieved in the time domain through the addition of a phase synchronized 80 MHz arbitrary waveform generator (AWG). The generated waveforms comprise frequency components that are multiples of the baseband fundamental frequency, and by controlling the relative magnitude and phase of these, constant and specific baseband impedance scenarios can be presented to a device and maintained across a wide bandwidth. The resulting waveforms are fed directly to the output of device through a 200W baseband power amplifier, increasing the signal amplitude to the levels required for load-pull.

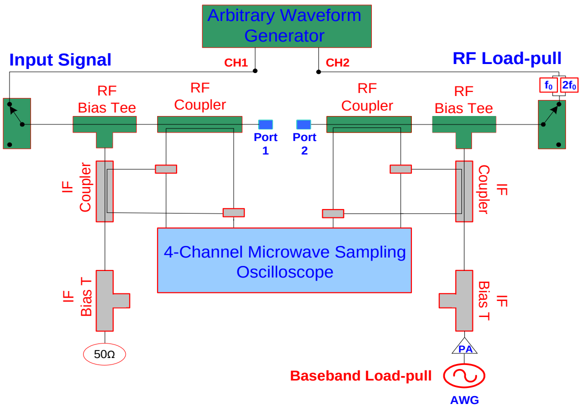

Fig. 3 Enhanced modulated waveform measurement system with the capability of active RF and IF load-pull.

The RF synthesizer used in the modulated waveform measurement system depicted in Fig. 3 is a two-channel Tektronix AWG7000 Arbitrary Waveform Generator, and its two independent yet coherent channels have been used here to synthesize both the modulated fundamental excitation and the complete modulated RF load-pull signal (comprising both fundamental band and harmonic band components) simultaneously, in the time domain. Through the addition of this instrument, the waveform measurement system is able to maintain independent and constant impedance control for each individual tone present across both IF and RF impedance environments, and over a wide modulation bandwidth. The enhanced modulated waveform measurement system depicted in Fig. 3 has been demonstrated in the first instance using wideband multi-sine stimuli to investigate the bandwidth dependent behavior of a CREE CGH40010 10W GaN HEMT device.

III. MULTI-TONE MEASUREMENTS AND INVESTIGATIONS

The device was characterized at using a 1 MHz modulated 2GHz carrier, and measurements were performed using a fully vector calibrated measurement system. The input stimulus comprised nine equally spaced tones of equal amplitude but with randomized phase. This was necessary to approximate a real wideband signal [8] with a peak-to-average power ratio (PAPR) of 9.54dB. The device was driven to deliver 39.5dBm peak envelope power (PEP) at approximately 1.5dB compression, and active IF load-pull was used to present the constant baseband impedance to all the significant baseband components (IF1-IF5) whilst in the first instance, the RF was actively terminated into a nominal impedance of 50Ω. The optimum IF impedance for the best linearity for this particular device, as has been identified using two-tone excitation in [3], lies outside the smith chart.

Fig. 4 illustrates a measurement where the broadband IF impedance was held constant for all baseband tones and swept over a measurement grid that includes the short circuit condition, and extends some way outside the Smith chart. For each of the measurement points, the bias and drive level was maintained constant. The optimum loads for $ACPR_L$ and $ACPR_H$ lie on the real axis and are almost identical in terms of their position and the degree of linearization they offer. The contours of $ACPR_L$ are plotted in Fig. 4 and show that at point B, the performance is found to be -43dBc, which is approximately a 25dB improvement over the classical short circuit case (point A).

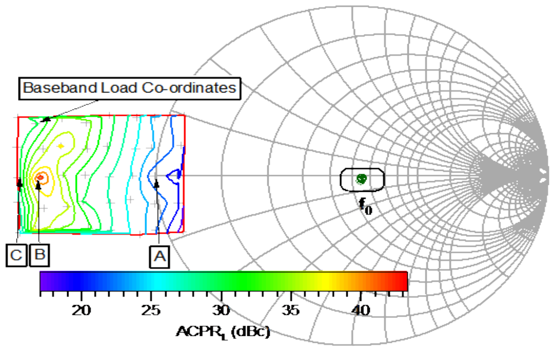

Fig. 4 Measured lower adjacent channel power linearity contours as a function of IF reflection coefficient (Γ_L).

The optimum load conditions for best linearity identified using this new sampling approach agree closely with the earlier documented results [3] on the same device, hence validating the approach. Fig. 5 depicts the baseband voltage and current waveforms required to present the device with the IF impedance of point B in Fig. 4. These relatively complex linearizing waveforms are clearly in-phase due to the purely real negative nature of the baseband termination and contain five baseband harmonics.

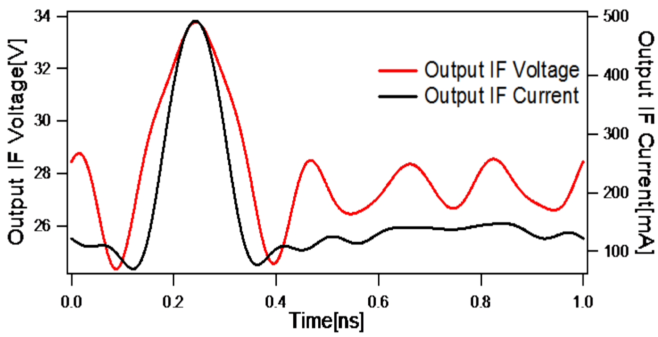

Fig. 5 Measured output baseband voltage and current at for best linearity at point –B.

IV. EMULATION OF CLASS-J IMPEDANCE ENVIRONMENT

To further demonstrate the enhanced broadband load-pull capabilities of the measurement system, a class-J mode was emulated by presenting established impedances [9] at the device package plane. The device was deep class-AB biased, and driven approximately 2dB into compression with a two-tone modulated excitation centered at 2GHz with a 4MHz tone spacing. An optimum reactive fundamental impedance was presented to all fundamental tones and a suitably phased reactive second harmonic impedance termination was

presented to the tones around the 2nd harmonic. The third harmonic components were terminated arbitrarily.

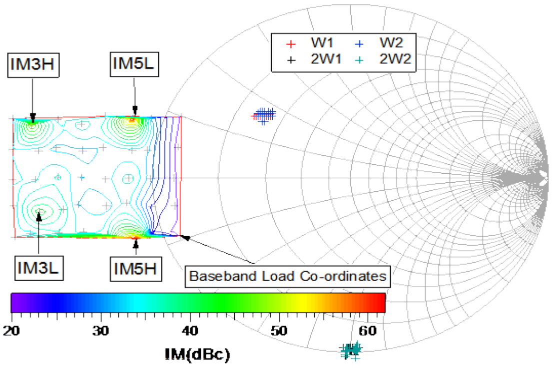

Fig. 6 Measured IM linearity contours as a function of IF reflection coefficient (Γ_L) for a class-J emulated RF impedance environment.

This analysis was specifically designed to investigate the effectiveness of baseband linearization techniques for novel PA modes and architectures, so as in the previous analysis, the impedance presented to all baseband tones was swept over a measurement around the short circuit condition. Selected inter-modulation distortion (IMD) contours are plotted in Fig. 6, which in this case show an interesting result - different non-real optima for different IMD terms. The ability of the system to maintain broadband baseband, fundamental and second harmonic loads is critical. This capability is evident in Fig.6 where the second and fundamental loads for all 40 baseband points are overlaid on the same smith chart - the variation and dispersion in these loads can be seen to be minimal and in terms of normalized Cartesian coordinates, this was measured to be in the region of 0.6%(1SD) for both fundamental and second harmonic loads.

V. CONCLUSION

An enhanced modulated waveform measurement system has been demonstrated that allows the emulation of novel PA modes and architectures, including for example class-J and envelope tracking respectively. Direct observation of the effects of baseband impedance variations is now possible over wide bandwidths, and under complex multi-sine excitations. Measurement speed and dynamic range have both been dramatically improved through the adoption of a new technique, here referred to as 'windowing', that allows the capture of a complete modulation cycle in a time efficient way and whilst employing the full capabilities of the sampling oscilloscope used.

The enhanced measurement system has been verified and validated through comparison with previous observations using earlier systems; relating to identification of optimal baseband impedances for linearity [3]. The true benefit of this enhanced system becomes apparent through the broadband emulation of a class-J mode of operation however, where initial results suggest that there exist separate optimum impedances for suppression of IM distortion products, and it is felt that this key observation may have significant implications for modern broadband PA design approaches.

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